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Centre for Alternate Fuel Utilization

ASSESSMENT OF AUTO-REGENERATION OF DIESEL PARTICULATE FILTERS BY FUEL ADDITIVE(S)

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Progress Report No. 4422/3
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1. SUMMARY

An evaluation of the performance of ceramic diesel particulate filters (DPF's) with manganese/copper fuel additive over a typical mining duty cycle has been completed. With fuel additive, in a concentration of 80 mg manganese and 20 mg copper per litre of diesel fuel, the filters can be expected to auto-regenerate over the MTU-LHD cycle. The manganese/copper additive does not significantly change emissions of SO_2/SO_4 and aldehydes. A substantial decrease in the Ames mutagenic activity is observed when using DPF's in combination with the fuel additive compared to uncontrolled diesel exhaust.

2. INTRODUCTION

An evaluation of two organo-metallic fuel additives for their effectiveness in lowering the ignition temperature of diesel particulate was summarized in a previous progress report (ORF Progress Report No. 4422/2). It was suggested in the report that manganese/copper fuel additive be selected over manganese alone on the basis of improved performance for reducing the exhaust backpressure rise rate and low particulate ignition temperature. The high treatment level of manganese/copper (80 mg Mn + 20 Mg Cu/L of fuel) resulted in a 44% reduction of the exhaust backpressure increase rate and a reduction in particulate ignition temperature to 345°C under certain engine conditions. A primary ignition temperature of 252°C was observed using manganese/copper additive with the ceramic diesel particulate filter (DPF) installed in a remote location. It is suspected that this primary ignition temperature is attributable to the combustion of the soluble organic fraction of the diesel particulate material.

Test results presented in the previous progress report also showed that the fuel additive did not appreciably reduce the in-cylinder production of diesel particulate material. This characteristic tends to suggest that the reduction in exhaust backpressure build-up rate is due to the partial regeneration of particulate on the DPF.

All of the test results previously presented were obtained at steady-state engine operating conditions. These tests allowed for a reasonable comparison of the relative performance of the two additives at the high and low treat levels. However, a complete assessment of the performance of the manganese/copper additive over transient engine operating conditions was necessary.

This report summarizes the results of the final task under this program where the manganese/copper fuel additive was evaluated over a load-haul-dump (LHD) duty cycle. The test results presented herein compare the effects of this additive to untreated diesel fuel with respect to emissions, DPF regeneration capability and internal DPF temperature characteristics. It was not the intent of this study to determine the effects of the fuel additive on the engine fuel injection system and/or the combustion chamber.

3. TEST EQUIPMENT AND PROCEDURE

Engine tests under the previous project task were conducted on a Deutz F8L 413 F/W diesel engine. It was necessary, however, to carry out the transient engine tests on a separate Deutz F8L 413 F/W engine with identical engine characteristics. The following sub-sections describe the equipment and instrumentation that was used to conduct the transient engine tests and emissions tests.

3.1 Dynamometer

An Eaton Model AD-8121 Eddy Current dynamometer is used to absorb the power generated by the engine. This dyno is a wet gap type capable of absorbing 373 kW at 5000 RPM and has an inertia of 46 lb.ft^2. Torque is measured using a Lebow load cell connected to the trunnion mounted dynamometer casing. The dynamometer operation can be manually controlled in a speed or torque mode via a stand-alone dyno exitation controller. Dynamometer bearing lubrication is provided by gravity fed oil reservoirs. A Hayes-Dana driveshaft with rubber element absorption is used as a coupling between the engine and dyno.

3.2 Computer Control System

The heart of the dynamic test facility lies in the computer control system. This system uses a Hewlett-Packard 1000 series E computer with 128K of memory and is coupled with a HP disc drive unit. Input/output interface is performed with Computer Products I/O equipment.

All programs are stored on an HP 7900 disc unit with measured and calculated data displayed on the operator console. The console is also used for entering operation commands concerning the test cell. During automatic control the system reads engine speed and torque ten times per second and, if required, corrects via output signals ten times per second. The system has a programming capability for cycle testing known as the schedule builder.

The schedule builder is based upon a series of steps. A step is defined RPM, torque, ramp time, stay time, where ramp time is the length of time to change from one load speed condition to the next. Stay time is defined as the length of time to remain at a given load speed. The minimum ramp time is one second and the minimum stay time is zero seconds. Up to 198 steps are user definable, however, the system includes the capability of major and minor looping within a cycle.

3.3 Heavy Duty Diesel Emissions Test Facility

The sampling and measurement of diesel exhaust emissions has presented many problems with respect to obtaining representative data that will correlate to conditions that occur in the underground mining environment. Chemical and physical reactions with certain species of diesel exhaust emissions take place after the exhaust has been released from the engine exhaust system. Specifically, particulate agglomeration in the soluble and insoluble form occur as the exhaust temperature is lowered to promote condensation of the soluble organic material. Formation of nitrogen dioxide (NO_2) from nitric oxide (NO) is a characteristic reaction in diesel exhaust as it is released from the exhaust system. These reactions have necessitated the need for a representative diesel exhaust sampling and analysis system. EPA has standardized such a system for engine certification procedures.

In an effort to keep abreast of these changes, ORF has installed, and commissioned a heavy duty diesel emissions test facility (Figure 4). The primary purpose of this facility is the measurement of emissions from diesel engines which are part of the dynamic test facility. The facility is comprised of two major systems; the dilution tunnel system and the analytical system. The following sub-sections describe the systems.

3.4 Dilution Tunnel System

There are basically two types of dilution tunnels available for the sampling of diesel exhaust emissions. One uses a single dilution method, the other a double dilution. ORF has selected a double dilution tunnel from a flexibility and cost standpoint. With a double dilution system the primary air mover can be downsized considerable to meet the temperature criteria necessary in dosigning such a system. The system comprises of three basic sections as described below.

3.4.1 Dilution Tunnel

The dilution tunnel consists of a 25.4 cm inside diameter primary tunnel and a 10.2 cm inside diameter secondary tunnel. All tunnel components are fabricated of stainless steel. Engine exhaust enters the primary tunnel via an upstream facing 10.2 cm nozzle. Dilution air flows past the nozzle and the resultant counter current flow enhances mixing of the exhaust with the air. Figure 1 illustrates a schematic for the emissions test facility. The primary tunnel has been engineered to provide a Reynolds number of more than 4000 to provide sufficient turbulence of the diluted exhaust. A fine mesh screen prevents large foreign objects from entering the primary tunnel.

Three sample probes are located approximately 2.5 meters downstream of the exhaust inlet. The first probe is used to transfer a portion of the primary tunnel exhaust to the secondary tunnel. The second probe is used for sample transport to the heated hydrocarbon analyzer and the third probe is dedicated to the other gaseous analyzers. Maximum allowable primary tunnel gas temperature at the sample probes is 190°C. A specially designed acoustic chamber was installed at the primary tunnel inlet to minimize engine exhaust and air mover noise in the vicinity of the test facility.

The secondary tunnel can be used to further dilute the sample from the primary tunnel to maintain a sample filter that will not exceed the maximum allowable 52°C. Three sample filters and one bypass filter are connected to the outlet of the secondary tunnel. The filter holders accept 70 mm diameter filters (Pallflex T60A20) and produce a 50 mm diameter stain area.

Secondary, or backup filters, are used to remove any particulate material that has passed the primary filter. Any one of the four filters can be selected manually or automatically from the particulate console. Automatic sequencing of the filter is achieved using computer activated relays or using a programmable sequence timer. The particulate console, also contains an air pump and protective filters for sampling diluted exhaust. A second pump is

used to provide pre-filtered air to the secondary tunnel when further dilution is required. Mass flows of sample gas and secondary dilution air are measured and controlled using mass flow controllers (Tylan Model FC202). These controllers are state-of-the-art devices which continuously monitor and correct the mass flow to maintain a proportional sampling rate, regardless of gas temperature and pressure. Accumulated dilution and sample gas flows are displayed using integrators, one set for each of the sample filters. The particulate console also contains a temperature measuring device to allow for recording of a variety of temperature stations, especially the primary and secondary tunnel gas temperatures.

3.4.2 Heat Exchanger

According to EPA specifications, the primary tunnel gas temperature must be adjusted to 43°C in order to provide constant gas density conditions to the primary air mover. In order to achieve a 147°C gas temperature drop, a tube and shell heat exchanger is located between the primary dilution tunnel and air mover. A 227 L/min water pump recirculates water through the shell side of the heat exchanger while primary tunnel exhaust gas is passed through the tube side. During testing of duty cycles with high load factors, the primary tunnel gas temperature is well above 43°C. In these cases the heat exchanger is used solely to cool the gas and this is achieved by adding cold water to the recirculating water loop. Thermostatically controlled, air actuated, water valves allow water to enter the system and a check valve discharges an equal volume of warm water. A second heat exchanger which is steam heated can be used to raise the water temperature to 43°C (in the case of low load factor duty cycles).

3.4.3 Air Mover

The primary tunnel gas flow is normally maintained at 510 standard cubic meters per minute (SCMM) with a high capacity positive displacement blower. This blower is a roots type and uses a 22 kW electric motor as a drive. Excessive noise, characteristic of these blowers, is reduced using a Donaldson muffler.

3.5 Gas Analysis

The gas analysis system is comprised of a hydrocarbon console and a main analysis console. Filters, housed in the heated hydrocarbon console, are used to remove particulate matter from the sample gas stream. A Beckman, Model 402, heated hydrocarbon analyzer continuously measures gaseous hydrocarbons (as methane) at a temperature of 190°C using a flame ionization detector. Background (ambient air) hydrocarbon concentrations are determined by sampling the dilution air at the primary tunnel. Concentrations of hydrocarbons in the dilution air are subtracted from the primary tunnel concentration to obtain hydrocarbon concentrations that are attributable to engine exhaust.

The main analysis console contains the NO, CO, CO_2 and heated NO_x analyzers. Two sample pumps are used to provide sample gas to the various analyzers. The following analyzers are used.

- NO_x - Beckman Model 955 heated chemiluminescent analyzer.
- NO - Beckman Model 951A chemiluminescent analyzer.
- CO - Beckman Model 867 non-dispersive infra-red.
- CO_2 - Beckman Model 864 non-dispersive infra-red.

Three calibration gases are used to span each analyzer for a given concentration range. These gases can be selected by push buttons on the main analysis console front panel. Strip chart recorders are used to display analyzer outputs on a continuous basis. Heated lines are used to keep the sample temperature well above the gas dewpoint to minimize losses due to condensation. A Hankinson dryer, however, is used to remove sample gas moisture prior to the NO, CO, and CO_2 analyzers to prevent water interference.

4. SULFATES SAMPLING AND ANALYSIS

A series of sulfate tests were conducted with the DPF's installed on the engine during operation with diesel fuel, diesel fuel with manganese/copper additive. Tests were conducted using the controlled condensation sampling system. This system, illustrated in Figure 2, allows for the quantitative collection of sulfates ($SO_4^=$) and sulfur dioxide (SO_2) from hot exhaust gas streams. The sampling system withdraws diluted exhaust gas (11 L/min) through a glass probe maintained at 250°C, followed by a glass cooling coil, maintained at 70°C. The sulfate fraction is removed in the coil while sulfur dioxide is removed in a set of impingers, downstream of the coil. Impingers contain a 3% (v/v) hydrogen peroxide solution. Solutions are subsequently analyzed using a spectrophotometer to determine the sulfur concentrations.

5. ALDEHYDE SAMPLING AND ANALYSIS

Sampling for aldehydes was performed using a modified EPA Method 5 source sampling system with a portion of the diluted exhaust extracted from the primary dilution tunnel. The diluted sample gas was passed through impingers containing a 2,4 dinitrophenylhydrozone (2,4 DNPH) solution. Aldehydes passing through the impinger solution are formed into their respective hydrozone derivatives. Following a filtration and extraction procedure the samples were injected into a high performance liquid chromatograph (HPLC) with a C_{18} RP Ultrasphere ODS column utilizing CH_3CN and H_2O in a solvent programmed run. A mixture of eight carbonyl compounds derivatized with (2,4 DNPH) was used as a reference standard. An aliquot of 50 uL was used as an injection volume. UV detection at 365 nm was used.

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6. AMES TESTING AND ANALYSIS

A selected number of particulate samples were obtained during transient tests for subsequent Ames mutagenic screening tests using a dilution "tube" as shown in Figure 3.

A portion of the diesel exhaust is diverted through a heated sampling probe into the dilution tunnel. A calibrated high volume sampler was used as a primary air mover. The diesel engine exhaust mixes with the air and is passed through a 25 x 20 cm teflon coated filter followed by two sections of Polyurethane Foam (PUF).

The PUF's are installed after the filter in an attempt to capture the majority of organics passing through the filter. Dilution ratios as high as 20:1 can be achieved by controlling the sample blower speed with a variable power source, and sample flow with a sample valve adjustment, or a combination of both.

A set of 8 Hi-Volume filters and 2 polyurethane foam plugs were assayed for mutagenicity using the Ames Salmonella mutagenicity assay. The Salmonella tester strains used were TA-98 both with and without metabolic activation, TA-98NR and TA-98-1, 8 DN_6 the nitroreductase deficient strains without metabolic activation. Only two strains were used for the polyurethane sample because of limited amount of SOF available. The Hi-Volume filters and Polyurethane foam plugs (PUF) were extracted for 16 hrs with dichloromethane. The extraction solvent was then taken to dryness and the weight of the soluble organic fraction (SOF) determined. Samples were then dissolved in dimethyl sulfur/oxide (DMSO) to concentration of 2000 µg/mL and tested in the Ames assay. Testing was carried out between 0 and 1000 µg/plate to obtain dose-response data. The specific activity as revertant/µg was calculated from the linear position of the dose response curve.

7. BACK PRESSURE AND TEMPERATURE MEASUREMENTS

Dynamic exhaust backpressure measurements were recorded using a Viatran pressure transducer. Integration and conversion to engineering units of the transducers 5 VDC analog output signal was accomplished using a Norland 3001 Digital Processing Oscilloscope.

A malfunction of the Viatran caused us to revert to the H_2O manometers for pressure measurements. Measurement of exhaust backpressure using a water manometer over a transient conduction is very difficult. For this reason the MTU-LHD cycle was placed on "hold" and the speed/load adjusted to 2200 RPM/41 kW. Upon achieving engine and temperature stabilization the exhaust backpressure was recorded and the MTU-LHD cycle resumed.

DPF internal temperatures were recorded using an Apple IIe computer and 'K' type thermocouples.

All temperature measurement devices and methods were identical to that reported in Progress Report No. 4422/2, ES/CAFU/84-09.

8. MTU-LHD CYCLE

Transient engine testing was accomplished by using a load-haul-dump (LHD) cycle derived by John Johnson of Michigan Technological University (MTU). The cycle, designated as the MTU-LHD, is comprised of four modes as follows:

Mode 1 - driving into the drift from a cross-cut.
Mode 2 - loading at the face (mucking).
Mode 3 - hauling out of the drift from the face of the cross-cut.
Mode 4 - hauling from the cross-cut to the dump point; dumping, returning to the cross-cut.

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The average engine exhaust temperature for this 150 second cycle is approximately 350°C, corresponding to an average engine speed of 2164 RPM and torque of 315 Nm.

9. TEST RESULTS

9.1. Gaseous Emissions

A series of gaseous emissions tests were performed to establish exhaust characteristics for various loads at an engine speed of 2200 RPM. These tests were performed for engine operation with and without the manganese/copper fuel additive. Table I gives CO, CO_2, O_2, NO, NO_x, and NO_2 concentrations for engine operation on neat diesel and Table II for engine operation with the manganese/copper fuel additive. Carbon monoxide and hydrocarbon emissions increased slightly during tests with the manganese/copper fuel additive. This increase may not necessarily be attributable to the additive and may be a function of other variables (i.e. intake air temperature). Increases in NO_x were observed, primarily due to the significant increase in NO_2, when operations with the fuel additive. Again, this characteristic may be a function of other engine test conditions.

Table III gives the average concentrations of CO_2, CO, O_2, THC, NO_x, and NO for engine operation over the MTU-LHD cycle. The table gives emission results for engine operation with and without the manganese/copper fuel additive. Emissions of CO and THC were found to increase with the additives, however, NO_x emissions decreased substantially.

9.2 Particulate Emissions

Particulate test results for engine operation over the MTU-LHD cycle are presented in Table IV. The average soluble and insoluble particulate emissions measured for engine operation with fuel additive are similar to that measured in previous test programs. These results suggest that the ceramic DPF's are controlling particulate emissions with an efficiency of approximately 90%. For the fuel additive tests, the soluble particulate accounted for approximately 61% of the total particulate and insoluble particulate accounted for 39%.

Very high concentrations of soluble particulate were measured for the MTU-LHD cycle tests with no fuel additive present. These high concentrations may be attributable to improper fuel combustion or the presence of engine crankcase oil in the exhaust. The insoluble particulate concentration for these tests appears to be acceptable.

9.3 $SO_2/SO_4^=$ Emissions

Table V gives results of emissions tests conducted to determine $SO_2/SO_4^=$ emissions downstream of the Corning DPF's. Appendix A gives the computer printout of the test results. The manganese/copper fuel additive did not appreciably effect the SO_2 to $SO_4^=$ conversion on the DPF's based on average results for each of the two test series. Average test results show that the accountability of total fuel sulfur is excellent for the two series.

These test results confirm the suspicion that base metal fuel additives do not noticeably convert SO_2 to $SO_4^=$ in typical engine exhaust conditions.

9.4 Aldehyde Emissions

Results of the aldehyde emissions tests conducted for engine operation over the MTU-LHD cycle with and without fuel additives are presented in Table VI. These results show that the manganese/copper fuel additive with DPF's in the exhaust system did not effectively change the baseline diesel aldehyde emissions. Total aldehyde concentrations were 15.14 ppm and 14.45 ppm for engine operation with and without fuel additive. Formaldehyde accounts for approximately 50% of the total aldehydes measured.

9.5 Ames Bioassay

A series of filters were used to collect the dilute diesel exhaust particulate using a dilution tube sampling system for tests with fuel additive. The high volume sampler filters collected 117.6 mg of total particulate material of which 102.2 mg was the soluble organic fraction. Polyurethane foam filters (PUF's) used downstream of the high volume sampler filters, collected 52.3 mg of total particulate material. The soluble organic fraction accounted for 50.1 mg of the total.

The soluble organic fraction of the PUF's was determined to be non-mutagenic to tester strain TA-98 both in the presence and absence of metabolic activation. Soluble organic material extracted from the high volume sampler filters was negative and non-mutagenic for tester strain TA-98-1, 8 DNP_6 and only marginally positive for tester strain TA-98NR. These results tend to indicate the absence of significant amounts of nitro PAH's.

The soluble fraction collected on the high volume sampler filters gave a positive mutagenic response to Salmonella tester strain TA-98 both in the presence and absence of metabolic activation. Specific activities of 0.43 revertants per microgram without metabolic activation and 0.28 revertants per microgram with metabolic activation were determined for the sample.

Total mutagenic activity in the diesel exhaust downstream of the DPF's was 2946 revertants per cubic meter (without metabolic activation) for engine operation with manganese/copper fuel additive over the MTU-LHD cycle. With metabolic activation the mutagenic activity was determined to the 1918 revertants per cubic meter. These test results suggest that there is negligible, if any, pass-through of manganese and/or copper via the Corning DPF's.

9.6 DPF Build-Up Rates

The normal exhaust backpressure build-up rate was measured to be 0.352 Kpa/min with the engine operating on No. 1 diesel fuel.

Figure 4 gives the build-up rate for fuel additives over a series of six (6) cumulative backpressure tests. At the beginning of each days test the backpressure build-up rate is increased rapidly, possibly due to engine operating conditions not being achieved. Differences in the rise rate between the right and left bank is unexplainable, however, at the end of 27 hrs of operation the overall effect of the fuel additive can be observed. There appears to be no substantial rise in backpressure.

9.7 DPF Temperature Profiles

Measurement of the temperatures at various locations in the DPF revealed that no appreciable exotherms were occurring in the DPF during testing over the MTU-LHD cycle with manganese/copper fuel additive. Figures 5, 6 and 7 show the temperature profiles over a number of consecutive tests. No appreciable exotherms were observed at any measured point in the filter.

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TABLE I

Steady State Testing with Diesel Fuel

Exhaust Gaseous Concentrations

Engine Speed RPM	Engine Load kW	CO_2 %	O_2 %	CO ppm	THC ppm	NO_x ppm	NO ppm	NO_2 ppm	Fuel Consumption g/s
2200	41	4.1	15.3	108	68	388	382	6	4.60
2200	56	4.8	14.3	113	79	478	456	22	5.37
2200	71	5.6	13.1	126	75	546	527	19	6.16
2200	78	6.4	12.0	141	87	595	578	17	7.00
2200	93	7.2	10.8	161	82	653	628	25	7.85
2200	108	8.3	9.2	189	104	704	682	22	8.85
2200	123	9.3	7.8	235	104	727	717	10	9.78

TABLE II

Steady State Testing with Fuel Additive

Exhaust Gaseous Concentrations

Engine Speed RPM	Engine Load kW	CO_2 %	O_2 %	CO ppm	THC ppm	NO_x ppm	NO ppm	NO_2 ppm	Fuel Consumption g/s
2200	41	4.2	15.1	126	23	417	385	32	4.78
2200	56	5.0	14.0	139	26	505	461	44	5.62
2200	71	5.9	12.7	163	76	570	512	57	6.51
2200	78	6.3	12.1	161	78	607	538	69	6.73
2200	93	7.2	10.8	194	82	660	600	60	7.74
2200	108	7.9	9.8	213	100	708	647	61	8.41
2200	123	9.2	8.0	292	105	773	699	74	9.56

TABLE III

Average Gaseous Concentrations Over the MTU-LHD Cycle
With and Without Fuel Additives

Average Engine Speed RPM	Average Engine Load kW	CO_2 %	O_2 %	CO ppm	THC ppm	NO_x ppm	NO ppm	NO_2 ppm	Fuel Consumption g/s
			Ceramic Trap With Diesel						
2162	72	5.7	10.8	173	75	564	539	25	6.15
		Ceramic Trap With Fuel Additive							
2164	72	6.2	10.4	190	80	494	494	0	6.36

TABLE IV

Particulate Emission Rates and Concentration
Over the MTU-LHD Cycle

Condition	Average Engine Speed RPM	Average Engine Load kW	Soluble				Insoluble				Total				% Soluble	% Insoluble
			mg/m^3	g/h	g/kW.h	g/kg (fuel)	mg/m^3	g/h	g/kW.h	g/kg (fuel)	mg/m^3	g/h	g/kW.h	g/kg (fuel)		
With Fuel Additive	2164	69	1.27	0.83	0.0118	0.0361	0.84	0.55	0.008	0.024	2.11	1.4	0.020	0.060	60.0	40.0
			0.90	0.59	0.0083	0.0256	0.90	0.59	0.008	0.026	1.80	1.2	0.017	0.051	50.0	50.0
			1.38	0.90	0.0128	0.0392	0.49	0.32	0.005	0.014	1.86	1.2	0.017	0.053	73.9	26.1
	Average		1.18	0.77	0.0110	0.0336	0.74	0.49	0.007	0.021	1.92	1.3	0.018	0.055	61.3	38.7
Diesel Fuel	2162	72	17.58	11.31	0.1581	0.5106	1.34	0.87	0.012	0.039	18.92	12.2	0.170	0.550	92.9	7.1
			19.75	12.70	0.1776	0.5736	1.20	0.77	0.011	0.035	20.95	13.5	0.188	0.609	94.3	5.7
			18.32	11.79	0.1648	0.5323	.90	0.58	0.008	0.026	19.23	12.4	0.173	0.558	95.3	4.7
	Average		18.55	11.93	0.1668	0.5388	1.15	0.74	0.013	0.033	19.70	12.7	0.177	0.572	94.2	5.8

TABLE V

Average $SO_2/SO_4^=$ Emission Rates
and
Concentration Over the MTU-LHD Cycle

Condition	SO_2				$SO_4^=$			
	ppm	mg/m^3	g/h	g/kW.h	ppm	mg/m^3	g/h	g/kW.h
Diesel Fuel	36.1	96.0	61.4	0.859	1.01	4.00	2.56	0.0358
with Mn/Cu	43.1	114	73.1	1.02	1.02	4.04	2.59	0.0362
Fuel Additive	17.0	45.1	28.8	0.403	1.13	4.52	2.89	0.0404
Average	32.1	85.0	54.4	0.761	1.05	4.19	2.68	0.0357
Diesel Fuel	25.9	68.8	44.0	0.612	3.00	11.9	7.63	0.106
with No	33.0	87.6	56.1	0.780	1.94	7.70	4.93	0.0686
Additive	32.0	84.9	54.3	0.756	2.01	7.99	5.11	0.0711
Average	30.3	80.4	51.5	0.716	2.32	9.20	5.89	0.0819

TABLE VI

Average Aldehyde Concentrations
Over MTU-LHD Cycle

	Neat Diesel		Diesel & Additive (DPF)	
Aldehyde	ppm	$\mu g/m^3$	ppm	$\mu g/m^3$
Formaldehyde	6.95	8,670	7.00	8,751
Acetaldehyde	1.80	3,471	2.16	3,982
Acetone	3.91	10,879	4.38	10,191
I-But-Aldehyde	1.24	3,664	1.62	4,820
Meet Ketone	N.D.	-	N.D.	-
Cro-Aldehyde	N.D.	-	N.D.	-
Hex-Aldehyde	N.D.	-	N.D.	-
Benzaldehyde	N.D.	-	N.D.	-
Total Aldehydes	14.45	26,684	15.14	27,774

N.D. - Not Detectable

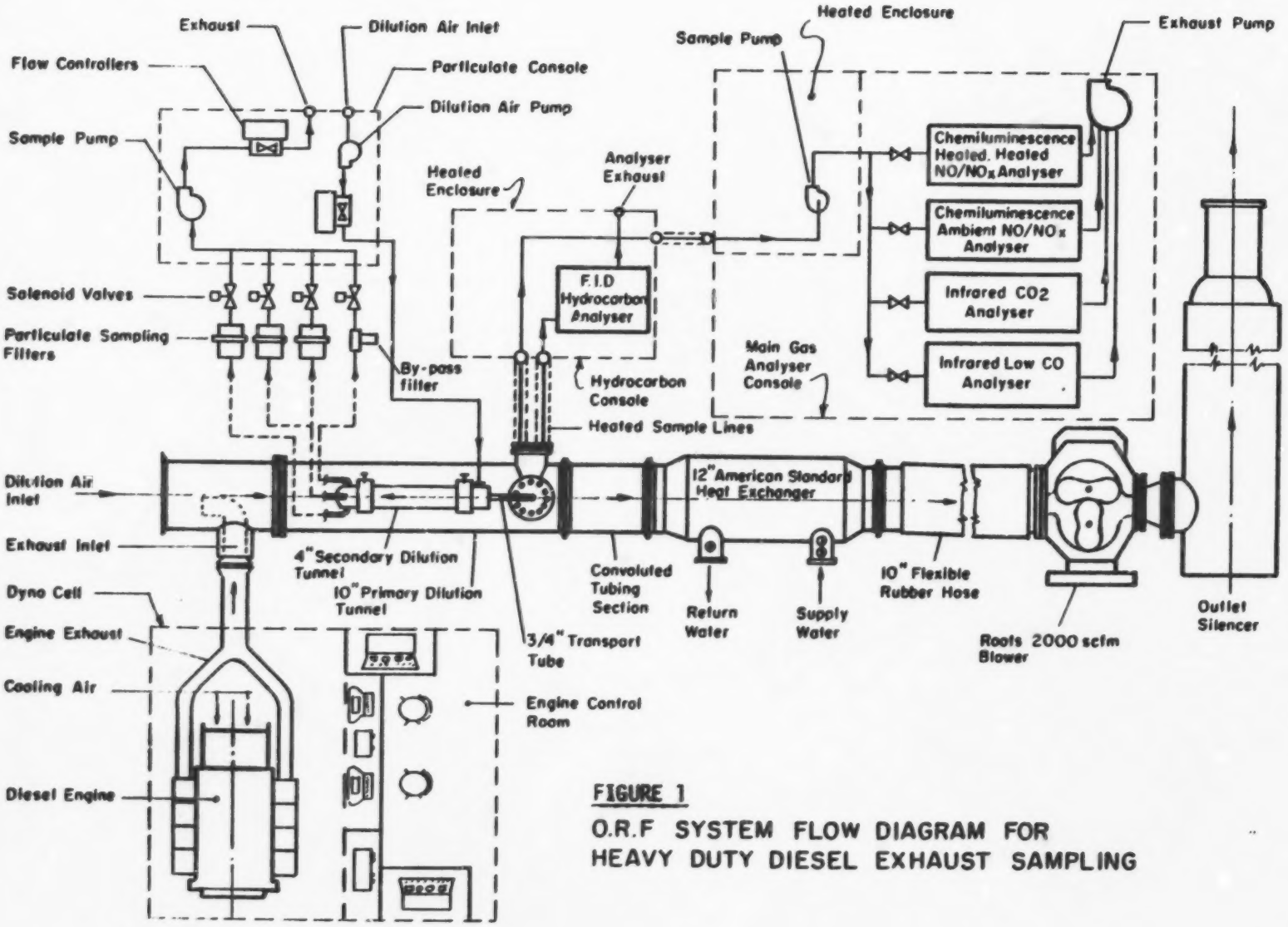


FIGURE 1

O.R.F SYSTEM FLOW DIAGRAM FOR HEAVY DUTY DIESEL EXHAUST SAMPLING

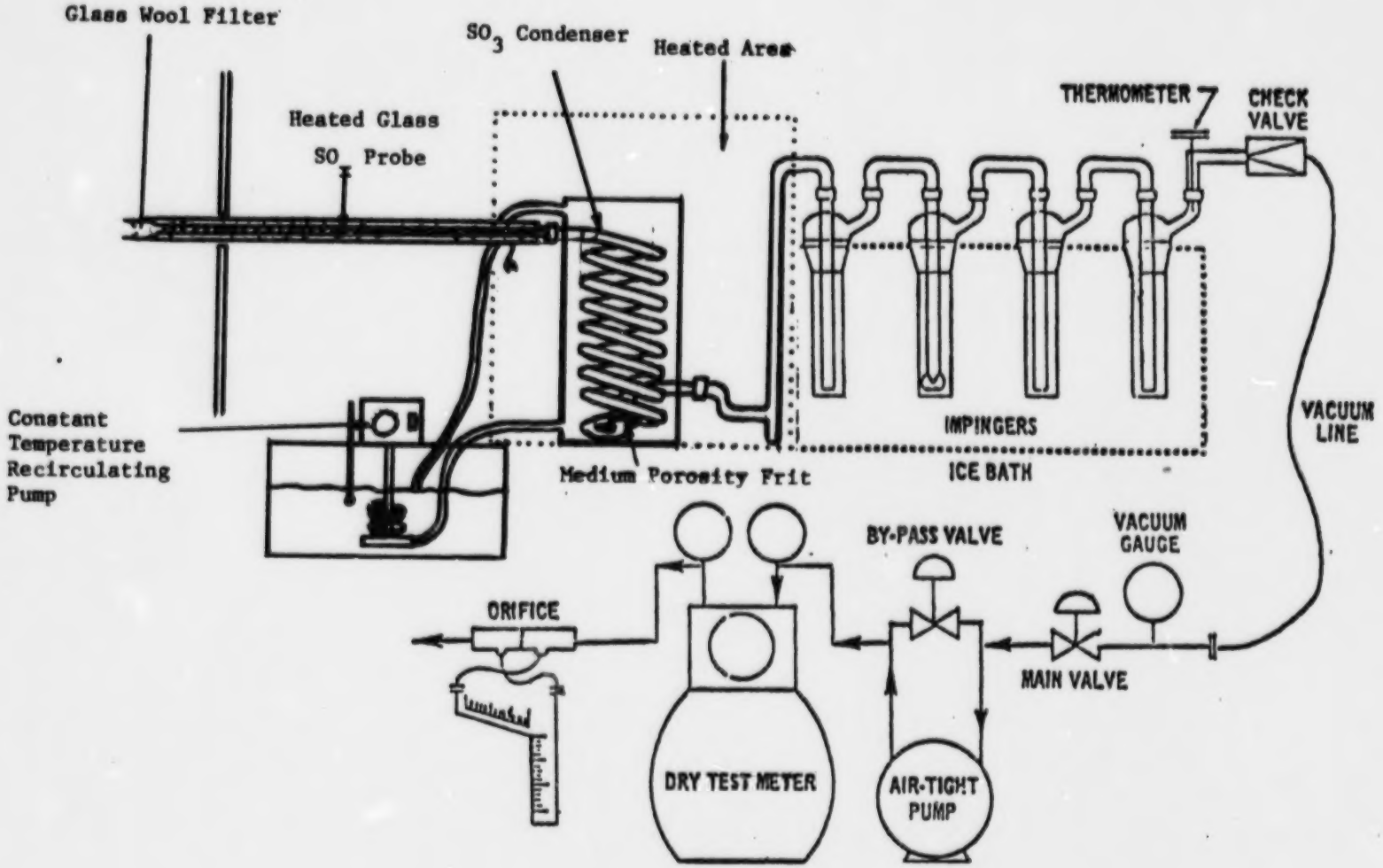


FIGURE 2 - Controlled Condensate

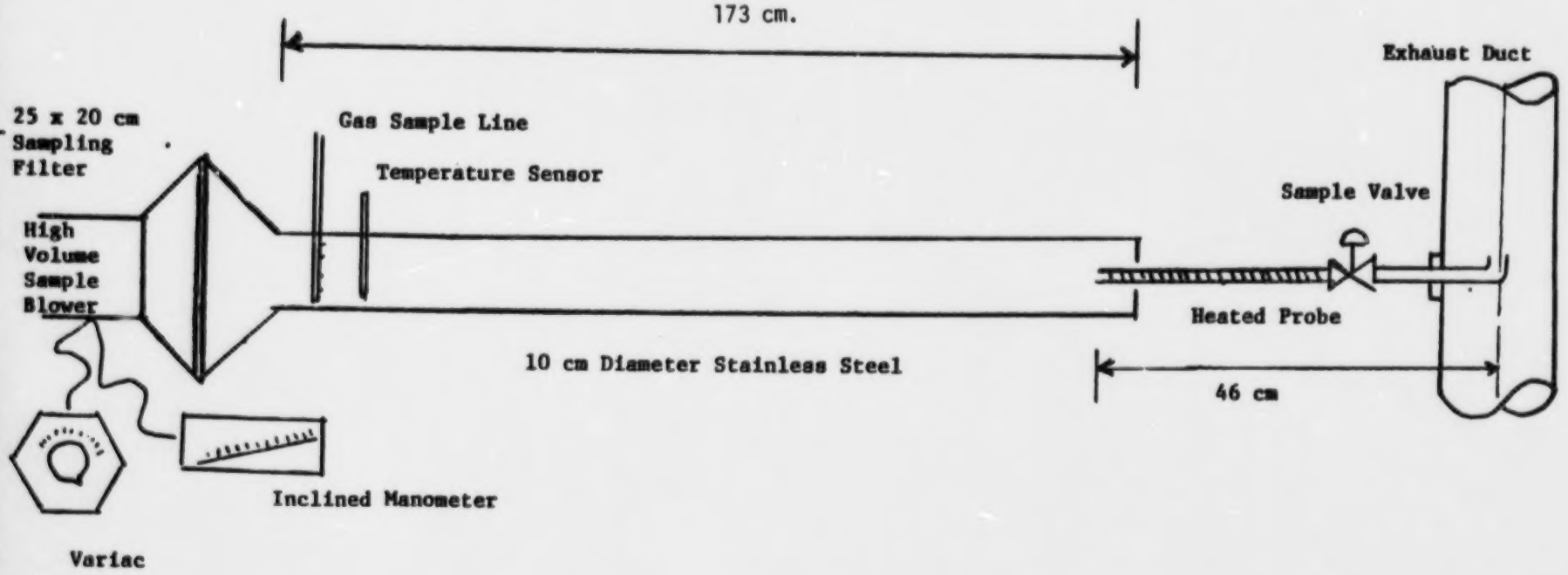


FIGURE 3: Dilution Tube

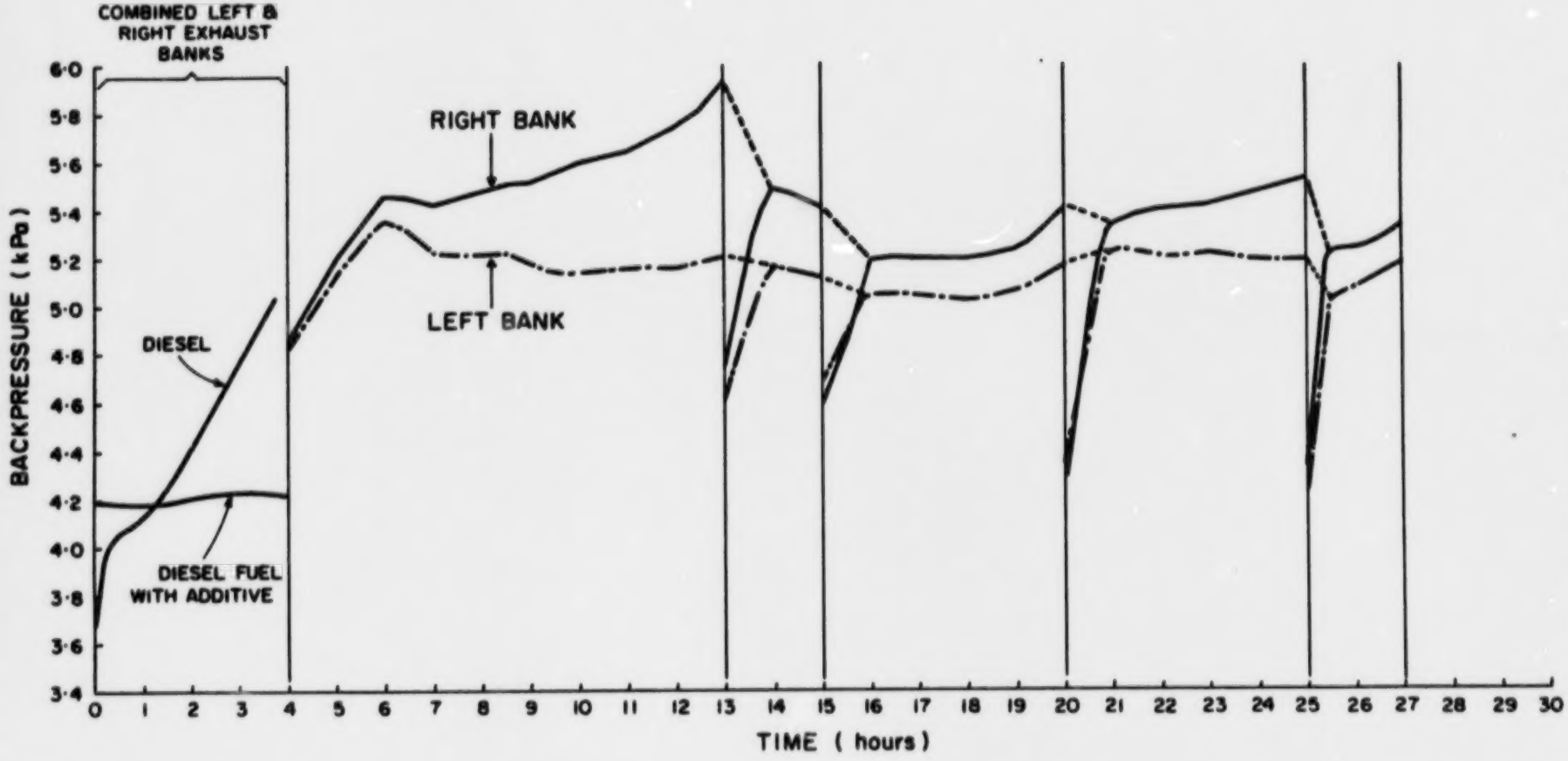


FIGURE 4. EXHAUST BACKPRESSURE vs TIME OVER MTU-LHD CYCLES.

FIGURE 5: Inlet and Outlet DPF Temperature Profiles Over MTU-LHD Cycle (With Fuel Additive)

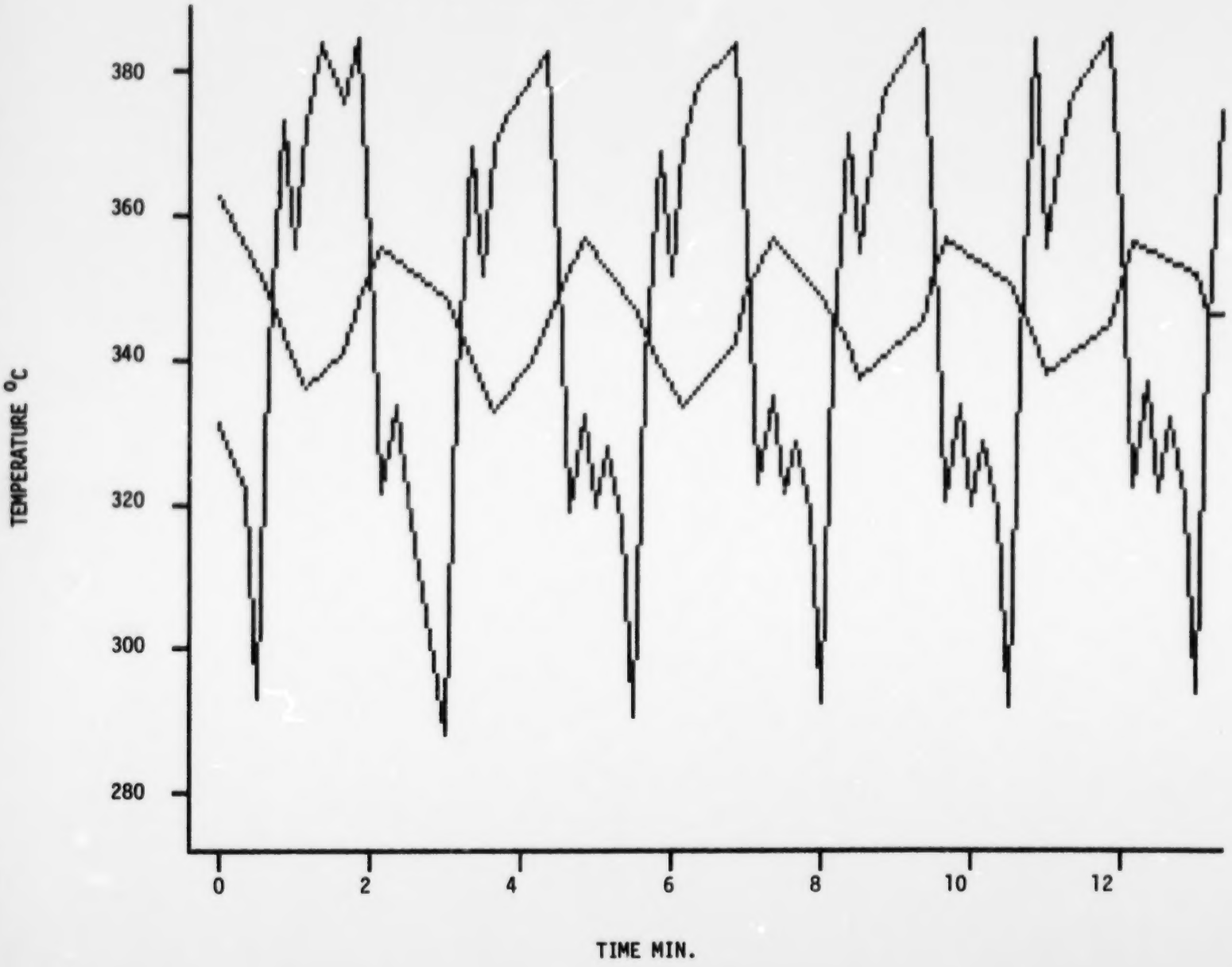


FIGURE 6: Vertical DPF Temperature Profile Over MTU-LHD Cycle (With Fuel Additive)

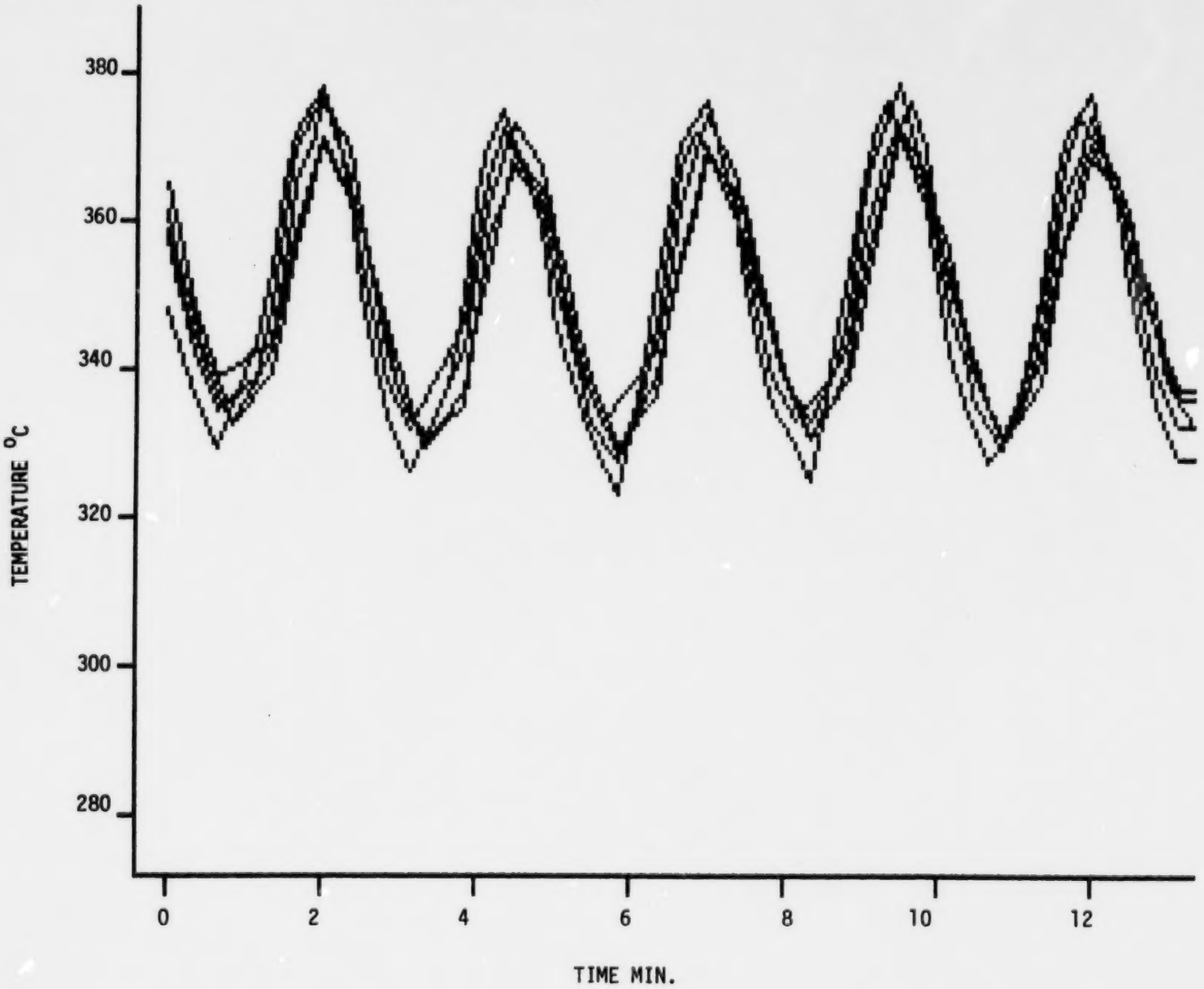
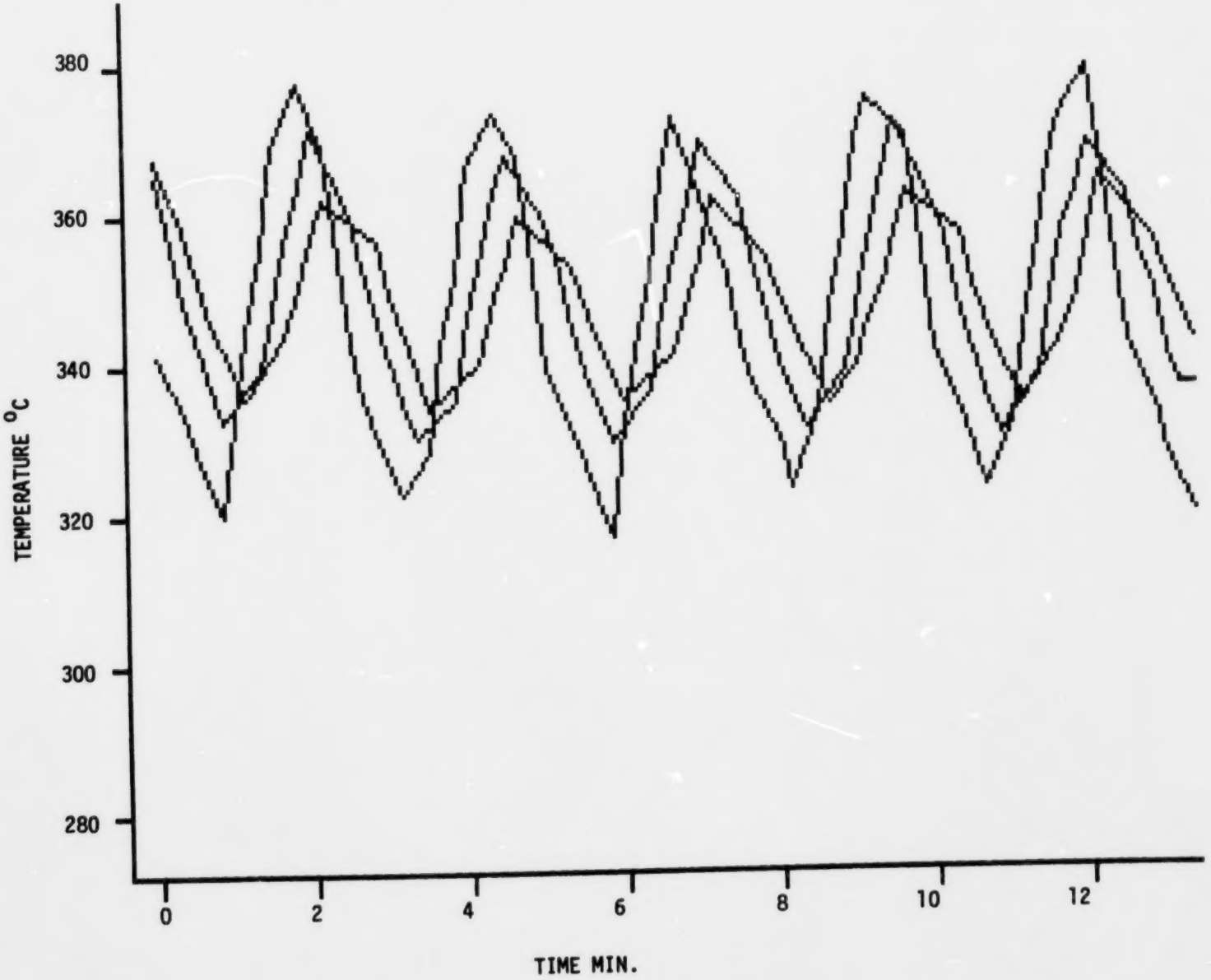


FIGURE 7: Horizontal DPF Temperature Profile Over MTU-LHD Cycle (With Fuel Additive)



APPENDIX A

SO_2/SO_4 Emissions

SO2/SO4 EMISSIONS

TEST NAME: DIESEL SULFATE
TEST # 1
DATE: FEB 22/1984
ENGINE LOAD SPEED (RPM/lb.ft)= 2163/23[A]
CELL #5
ENGINE SERIAL #6284019

VOLUME OF SAMPLE FOR SO2 (ml)= 304
VOLUME OF SAMPLE FOR SO4 (ml)= 162
CONC OF SO2 (ug/ml)= 32.22
CONC OF SO4 (ug/ml)= 6.99
SAMPLE DILUTION FOR SO2= 1
SAMPLE DILUTION FOR SO4= 1
VOLUME OF SAMPLE (cu.ft)= 17.7
% SULPHUR IN FUEL= .15
FUEL CONSUMPTION (kg/hr)= 22.18
EXHAUST FLOWRATE (cu.m/min)= 10.66
POWER (kW)= 71.86
DILUTION RATIO= 5.3

ppm THEOR [SO2+SO4] IN EXHAUST= 39.1456193
ppm MEASURED [SO2+SO4] IN EXHAUST= 28.9173533

CONCENTRATION IN RAW EXHAUST
25.9206796 ppm(SO2)
2.99667369 ppm(SO4)

EMISSION RATES FOR SO2
68.8138722 mg/cu.m
44.0133526 g/hr
.612487512 g/kW.hr
1.98437117 g/kg of fuel

EMISSION RATES FOR SO4
11.9295679 mg/cu.m
7.63015165 g/hr
.106180791 g/kW.hr
.344010444 g/kg of fuel

SO2/SO4 EMISSIONS

TEST NAME: DIESEL SULFATE
TEST # 2
DATE: FEB 22/1984
ENGINE LOAD SPEED (RPM/lb.ft)= 2163/234
CELL #5
ENGINE SERIAL #6284019

VOLUME OF SAMPLE FOR SO2 (ml)= 300
VOLUME OF SAMPLE FOR SO4 (ml)= 105
CONC OF SO2 (ug/ml)= 18.63
CONC OF SO4 (ug/ml)= 3.12
SAMPLE DILUTION FOR SO2= 1
SAMPLE DILUTION FOR SO4= 1
VOLUME OF SAMPLE (cu.ft)= 7.93
% SULPHUR IN FUEL= .15
FUEL CONSUMPTION (kg/hr)= 22.18
EXHAUST FLOWRATE (cu.m/min)= 10.66
POWER (kW)= 71.86
DILUTION RATIO= 5.3

ppm THEOR [SO2+SO4] IN EXHAUST= 39.1456193
ppm MEASURED [SO2+SO4] IN EXHAUST= 34.9477767

CONCENTRATION IN RAW EXHAUST
33.012731 ppm(SO2)
1.93504574 ppm(SO4)

EMISSION RATES FOR SO2
87.6417549 mg/cu.m
56.0556664 g/hr
.780067721 g/kW.hr
2.52730687 g/kg of fuel

EMISSION RATES FOR SO4
7.70329441 mg/cu.m
4.92702711 g/hr
.0685642514 g/kW.hr
.222138282 g/kg of fuel

SO2/SO4 EMISSIONS

TEST NAME: DIESEL SULFATE
TEST # 3
DATE: FEB 22/1984
ENGINE LOAD SPEED (RPM/lb.ft)= 2163/234
CELL #5
ENGINE SERIAL #6284019

VOLUME OF SAMPLE FOR SO2 (ml)= 308
VOLUME OF SAMPLE FOR SO4 (ml)= 103
CONC OF SO2 (ug/ml)= 16.63
CONC OF SO4 (ug/ml)= 3.12
SAMPLE DILUTION FOR SO2= 1
SAMPLE DILUTION FOR SO4= 1
VOLUME OF SAMPLE (cu.ft)= 7.5
% SULPHUR IN FUEL= .15
FUEL CONSUMPTION (kg/hr)= 22.18
EXHAUST FLOWRATE (cu.m/min)= 10.66
POWER (kW)= 71.86
DILUTION RATIO= 5.3

ppm THEOR [SO2+SO4] IN EXHAUST= 39.1456193
ppm MEASURED [SO2+SO4] IN EXHAUST= 33.9961327

CONCENTRATION IN RAW EXHAUST
31.9891156 ppm(SO2)
2.00701716 ppm(SO4)

EMISSION RATES FOR SO2
84.9242745 mg/cu.m
54.3175659 g/hr
.755880406 g/kW.hr
2.44894346 g/kg of fuel

EMISSION RATES FOR SO4
7.98980806 mg/cu.m
5.11028123 g/hr
.0711144062 g/kW.hr
.230400416 g/kg of fuel

SO2/SO4 EMISSIONS

TEST NAME: FUEL ADDITIVE SULFATE
TEST # 1
DATE: FEB 22/1984
ENGINE LOAD SPEED (RPM/lb.ft)= 2161/233
CELL #5
ENGINE SERIAL #6284019

VOLUME OF SAMPLE FOR SO2 (ml)= 310
VOLUME OF SAMPLE FOR SO4 (ml)= 100
CONC OF SO2 (ug/ml)= 54.27
CONC OF SO4 (ug/ml)= 4.68
SAMPLE DILUTION FOR SO2= 1
SAMPLE DILUTION FOR SO4= 1
VOLUME OF SAMPLE (cu.ft)= 21.79
% SULPHUR IN FUEL= .15
FUEL CONSUMPTION (kg/hr)= 22.64
EXHAUST FLOWRATE (cu.m/min)= 10.66
POWER (kW)= 71.49
DILUTION RATIO= 5.3

ppm THEOR [SO2+SO4] IN EXHAUST= 39.9574762
ppm MEASURED [SO2+SO4] IN EXHAUST= 37.1707216

CONCENTRATION IN RAW EXHAUST
36.1646958 ppm(SO2)
1.00602588 ppm(SO4)

EMISSION RATES FOR SO2
96.0095486 mg/cu.m
61.4077073 g/hr
.858969188 g/kW.hr
2.71235456 g/kg of fuel

EMISSION RATES FOR SO4
4.00492524 mg/cu.m
2.56155018 g/hr
.035830888 g/kW.hr
.113142676 g/kg of fuel

SO2/SO4 EMISSIONS

TEST NAME: FUEL ADDITIVE SULFATE
TEST # 2
DATE: FEB 22/1984
ENGINE LOAD SPEED (RPM/lb.ft)= 2161/233
CELL #5
ENGINE SERIAL #6284019

VOLUME OF SAMPLE FOR SO2 (ml)= 336
VOLUME OF SAMPLE FOR SO4 (ml)= 105
CONC OF SO2 (ug/ml)= 41.34
CONC OF SO4 (ug/ml)= 3.12
SAMPLE DILUTION FOR SO2= 1
SAMPLE DILUTION FOR SO4= 1
VOLUME OF SAMPLE (cu.ft)= 15.11
% SULPHUR IN FUEL= .15
FUEL CONSUMPTION (kg/hr)= 22.64
EXHAUST FLOWRATE (cu.m/min)= 10.66
POWER (kW)= 71.49
DILUTION RATIO= 5.3

ppm THEOR [SO2+SO4] IN EXHAUST= 39.9574762
ppm MEASURED [SO2+SO4] IN EXHAUST= 44.0747329

CONCENTRATION IN RAW EXHAUST
43.059186 ppm(SO2)
1.01554684 ppm(SO4)

EMISSION RATES FOR SO2
114.312949 mg/cu.m
73.114562 g/hr
1.02272433 g/kW.hr
3.22944179 g/kg of fuel

EMISSION RATES FOR SO4
4.04282758 mg/cu.m
2.58579252 g/hr
.036169989 g/kW.hr
.11421345 g/kg of fuel

SO2/SO4 EMISSIONS

TEST NAME: FUEL ADDITIVE SULFATE
TEST # 3
DATE: FEB 22/1984
ENGINE LOAD SPEED (RPM/lb.ft)= 2161/233
CELL #5
ENGINE SERIAL #6284019

VOLUME OF SAMPLE FOR SO2 (ml)= 312
VOLUME OF SAMPLE FOR SO4 (ml)= 105
CONC OF SO2 (ug/ml)= 31.41
CONC OF SO4 (ug/ml)= 6.24
SAMPLE DILUTION FOR SO2= 1
SAMPLE DILUTION FOR SO4= 1
VOLUME OF SAMPLE (cu.ft)= 27.05
% SULPHUR IN FUEL= .15
FUEL CONSUMPTION (kg/hr)= 22.64
EXHAUST FLOWRATE (cu.m/min)= 10.66
POWER (kW)= 71.49
DILUTION RATIO= 5.3

ppm THEOR [SO2+SO4] IN EXHAUST= 39.9574762
ppm MEASURED [SO2+SO4] IN EXHAUST= 18.1043227

CONCENTRATION IN RAW EXHAUST
16.9697636 ppm(SO2)
1.13455917 ppm(SO4)

EMISSION RATES FOR SO2
45.0511005 mg/cu.m
28.8146839 g/hr
.403058943 g/kW.hr
1.27273339 g/kg of fuel

EMISSION RATES FOR SO4
4.51660811 mg/cu.m
2.88882255 g/hr
.0404087641 g/kW.hr
.127598169 g/kg of fuel

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